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THE EFFECT OF POLYMER ADDITIVES  
ON THE  
CAVITATION THRESHOLD OF WATER

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\*MS Thesis directed by Lawrence A. Crum

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based upon cavitation nucleation from gas trapped in a crevice in a solid impurity present in the liquid. It was discovered that previous explanations of the effect of polymer additives on the cavitation threshold are incomplete and need to take certain physical parameters of the liquid into account as well as the mode of cavitation nucleation.



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## ABSTRACT

### THE EFFECT OF POLYMER ADDITIVES ON THE CAVITATION THRESHOLD OF WATER

BROSEY, JAMES EUGENE. B.S., David Lipscomb College, 1980. Thesis directed by Professor Lawrence A. Crum.

The effect of the polymer additives Polyox and Guar Gum on the acoustic cavitation threshold of water was studied as a function of polymer concentration and dissolved gas content. Cavitation thresholds were measured for water and different concentrations of Polyox and Guar Gum at various dissolved oxygen concentrations, using an ultrasonic technique. In this study, poor agreement was obtained for theoretical predictions based upon growth of a free air bubble, and good agreement was obtained for a theory based upon cavitation nucleation from gas trapped in a crevice in a solid impurity present in the liquid. It was discovered that previous explanations of the effect of polymer additives on the cavitation threshold are incomplete and need to take certain physical parameters of the liquid into account as well as the mode of cavitation nucleation.

#### ACKNOWLEDGEMENTS

I would like to thank Dr. L.A. Crum for his help and guidance, and the Office of Naval Research and the National Science Foundation for financial support while preparing this thesis. I would also like to thank my wife, Doni, who supported me throughout my stay in Graduate School.

## TABLE OF CONTENTS

	Page
LIST OF TABLES . . . . .	vi
LIST OF FIGURES . . . . .	vii
I. INTRODUCTION . . . . .	1
PURPOSE OF THE STUDY . . . . .	1
DEFINITION OF CAVITATION . . . . .	1
EFFECTS OF SURFACE TENSION ON CAVITATION THRESHOLDS . . . . .	2
II. EXPERIMENTAL ARRANGEMENTS . . . . .	4
III. EXPERIMENTAL PROCEDURE . . . . .	9
PREPARATION OF SOLUTIONS . . . . .	9
CAVITATION MEASUREMENTS . . . . .	10
SURFACE TENSION MEASUREMENTS . . . . .	10
VISCOSITY MEASUREMENTS . . . . .	11
IV. THEORY . . . . .	12
FREE AIR BUBBLE MODELS . . . . .	12
Blake's Model . . . . .	12
Apfel's Model . . . . .	13
HARVEY'S MODEL . . . . .	15
V. RESULTS AND DISCUSSION . . . . .	19
SURFACE TENSION REDUCTION BY ADDITION OF POLYMERS . . . . .	19
CAVITATION THRESHOLDS AS A FUNCTION OF CONCENTRATION . . . . .	19



	Page
VISCOSITY OF POLYOX AND GUAR GUM . . . . .	23
FREE BUBBLE THEORIES TESTED . . . . .	25
Blake's Theory . . . . .	25
Apfel's Theory . . . . .	28
HARVEY'S THEORY TESTED . . . . .	29
Cavitation thresholds as a function of dissolved oxygen concentration . . . . .	29
Cavitation threshold as a function of surface tension . . . . .	32
VI. ERROR ANALYSIS AND LIMITS OF ACCURACY . . . . .	34
VII. CONCLUSIONS . . . . .	38
SELECTED BIBLIOGRAPHY . . . . .	49
BIOGRAPHICAL SKETCH OF THE AUTHOR . . . . .	50

# LIST OF TABLES

Table	Page
1. Surface Tension versus Concentration in Polyethylene Oxide . . . . .	40
2. Surface Tension versus Concentration in Guar Gum . . . . .	41
3. Data Necessary to Calculate Viscosity in Polyox . . . . .	42
4. Data Necessary to Calculate Viscosity in Guar Gum . . . . .	43
5. Cavitation Threshold versus Dissolved Oxygen Concentration in Distilled Water . . . . .	44
6. Cavitation Threshold versus Polymer Concentration in Polyox . . . . .	45
7. Cavitation Threshold versus Polymer Concentration in Guar Gum . . . . .	46
8. Cavitation Threshold versus Dissolved Oxygen Concentration for 50 ppm Guar Gum . . . . .	47
9. Cavitation Threshold versus Dissolved Oxygen Concentration for 100 ppm Guar Gum . . . . .	48

## LIST OF FIGURES

Figure	Page
1. Photograph of the Experimental Apparatus . . . . .	6
2. Photograph of the Cavitation Cell . . . . .	7
3. Photograph of the YSI Dissolved Oxygen Meter and the Cenco-Du Nouy tensiometer . . . . .	8
4. Mathematical Model for Stabilization of a Gas Pocket on a Solid Impurity . . . . .	16
5. Mathematical Model for Nucleation of a Free Gas Bubble from a Gas Pocket on a Solid Impurity . . . . .	17
6. Variation of Surface Tension with Concentration of Polymer for Polyox and Guar Gum . . . . .	20
7. Variation of the Cavitation Threshold with Concentration of Polyox . . . . .	21
8. Variation of the Cavitation threshold with Concentration of Guar Gum . . . . .	22
9. Variation of Viscosity with Concentration of Polymer for Polyox and Guar Gum . . . . .	24
10. Variation of the Cavitation Threshold with Surface Tension in Polyox . . . . .	26
11. Variation of the Cavitation Threshold with Surface Tension in Guar Gum . . . . .	27
12. Variation of the Cavitation Threshold with Dissolved Oxygen Concentration in Polyox . . . . .	30
13. Variation of the Cavitation Threshold with Dissolved Oxygen Concentration in Guar Gum . . . . .	31

## INTRODUCTION

It is well known that the tensile strength of water is significantly less than the theoretical predictions. The reduced strength can be attributed to the fact that there exists within the bulk of the fluid numerous inhomogeneities that serve as nuclei for the onset of liquid rupture. These nuclei may take the form of free air bubbles, or pockets of gas that are stabilized within solid particles floating freely in the bulk of the liquid, or perhaps some other undiscovered nucleation mechanism. The tensile strength of a liquid can be obtained by measuring the negative acoustic pressure required to rupture the liquid. This negative acoustic pressure is called the acoustic cavitation threshold of the liquid.

The purpose of this experiment was to investigate the cavitation threshold of water as a function of polymer concentration, surface tension, dissolved gas concentration, and viscosity.

Cavitation, in the context of this study, will be defined as the expansion of a pre-existing nucleus to a size where macroscopic effects can be observed. One well known method of measuring the cavitation threshold was used in this experiment. The liquid was stressed dynamically by a stationary acoustic field. When the peak negative acoustic pressure amplitude was significantly large, the liquid ruptured and formed a rapidly growing vapor cavity that collapsed violently in the positive cycle of the acoustic pressure. This type of cavitation is termed transient

cavitation in that the event is self-destructive. The cavity collapse is significantly violent to create an intense shock wave that in turn can cause the walls of the containing vessel to emit an audible sound. If the collapse occurs in the vicinity of a solid boundary, destructive effects can be realized and, accordingly, cavitation is in general an undesirable event.

It has been previously shown that the cavitation index associated with submerged water jets<sup>1</sup>, and the flow of water past a solid body<sup>2</sup> has been greatly affected by the addition of long-chain polymers such as Polyethelene Oxide and Guar Gum. It has also been shown that the addition of these polymers to water decreases the drag on solid bodies moving through the solution. The molecular weight of these polymers is very large, as high as 300,000 for Guar Gum.

Since the surface tension appears to have a significant effect on the cavitation threshold, and since polymer additives tend to reduce surface tension, this experiment was devised to examine the effect of dilute polymer additives on the cavitation threshold of water. In this study, it was discovered that the effects of polymer additives on the cavitation threshold of water can be explained by using a modified version

---

<sup>1</sup>Hoyt, J.W., J. Fluids Engr. 106-112 (1976).

<sup>2</sup>Ellis, A.T., J.G. Waugh, and R.Y. Ting, J. Basic Engr. Series D 92, 459-466 (1970).

of a theory originally developed by Apfel<sup>3</sup> and later modified by Crum<sup>4</sup>. This theory leads to an equation that can adequately predict the effect of the polymer additives on the acoustic cavitation threshold as a function of several liquid parameters.

This experiment also demonstrates that the effects of surface tension, dissolved gas concentration, and viscosity on the cavitation threshold can be correctly predicted. The polymers used in this study are Polyethylene Oxide (Polyox) and Guar Gum.

A series of measurements of the cavitation threshold were made using distilled water, concentrations of Polyox ranging from 1 part per million to 100 parts per million (ppm), and concentrations of Guar Gum ranging from 25 ppm to 300 ppm by weight. For each solution, various dissolved gas concentrations ranging from 16% to 85% were also used. The appropriate theory was then applied to these data and a comparison made between the measured and predicted results. Excellent agreement was obtained between theory and experiment for the range of data used.

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<sup>3</sup>Apfel, R.E., Acoust. Soc. of Amer. 48, 1179-1186, (1970).

<sup>4</sup>Crum, L.A., Nature 278, 148-149, (March 8, 1979).

## EXPERIMENTAL ARRANGEMENT

The cavitation threshold of distilled water and solutions containing varying concentrations of two different polymer additives were measured experimentally using an ultrasonic technique. A detailed description of this technique will be given in the experimental measurement section.

A Hewlett Packard test oscillator, model number 651B, was used to produce a stable sine wave output signal. This device covers a frequency range from 10 Hz to 10 MHz, and has an adjustable output signal that spans from 10  $\mu$ V to 3.16 V into a 50  $\Omega$  connector for low source impedance. Measurements were taken with the frequency set at 78.0 kHz.

The signal from the Hewlett Packard test oscillator was split into two parts. One signal triggered a T912 10 MHz storage oscilloscope and was displayed on channel 1. The other half was used as the input signal to the cavitation cell and was amplified by an ENI power amplifier, model number 1140LA, before being introduced to the cell.

The frequency and the amplitude of the signal from the oscillator were measured by a Hewlett Packard universal counter, model number 5314A, and a Hewlett Packard digital multimeter, model number 3466A, respectively.

The cavitation cell was a hollow Barium-Titanate piezoelectric cylinder of 7.5 cm height and 7.5 cm outside diameter. It was driven at one of its harmonic modes, so that cavitation occurred in the center of the liquid, and not on the walls. Cemented to the bottom of the transducer

was a thin (40 microns) glass window that acted as a pressure-release surface. A lid was fashioned from a plexiglass holder and a second thin glass window. Attached to the bottom of the window was a small piezoelectric disc, 0.7 cm in diameter, that was used as an externally-mounted hydrophone to monitor the acoustic pressure generated within the cell. The external disc was calibrated in terms of a previously calibrated hydrophone that was inserted into the bulk of the fluid.

The voltage output from the hydrophone was relayed to a Hewlett Packard amplifier, model number 465A, for a gain of 20 dB before the signal was displayed on channel 2 of the storage oscilloscope. This output signal was read with a Heathkit AC voltmeter, model number IM-5238. A photograph of the experimental apparatus is shown in Fig. 1, and a photograph of the cavitation cell is shown in Fig. 2.

The precise dissolved gas concentrations in the solutions were measured by first reducing the gas concentration with a vacuum pump, and then measuring the dissolved gas concentration with a YSI dissolved oxygen meter, model number 51B, accurate to 2%.

The surface tensions of the polymer solutions were measured with a Cenco-Du Nouy tensiometer, accurate to the nearest 0.05 dynes/cm. The apparatus for measurement of the dissolved oxygen content and the surface tension is shown in Fig. 3.

Finally, to measure the viscosity, a modified Fenske viscometer, devised from a modified Ostwald viscometer, was used.



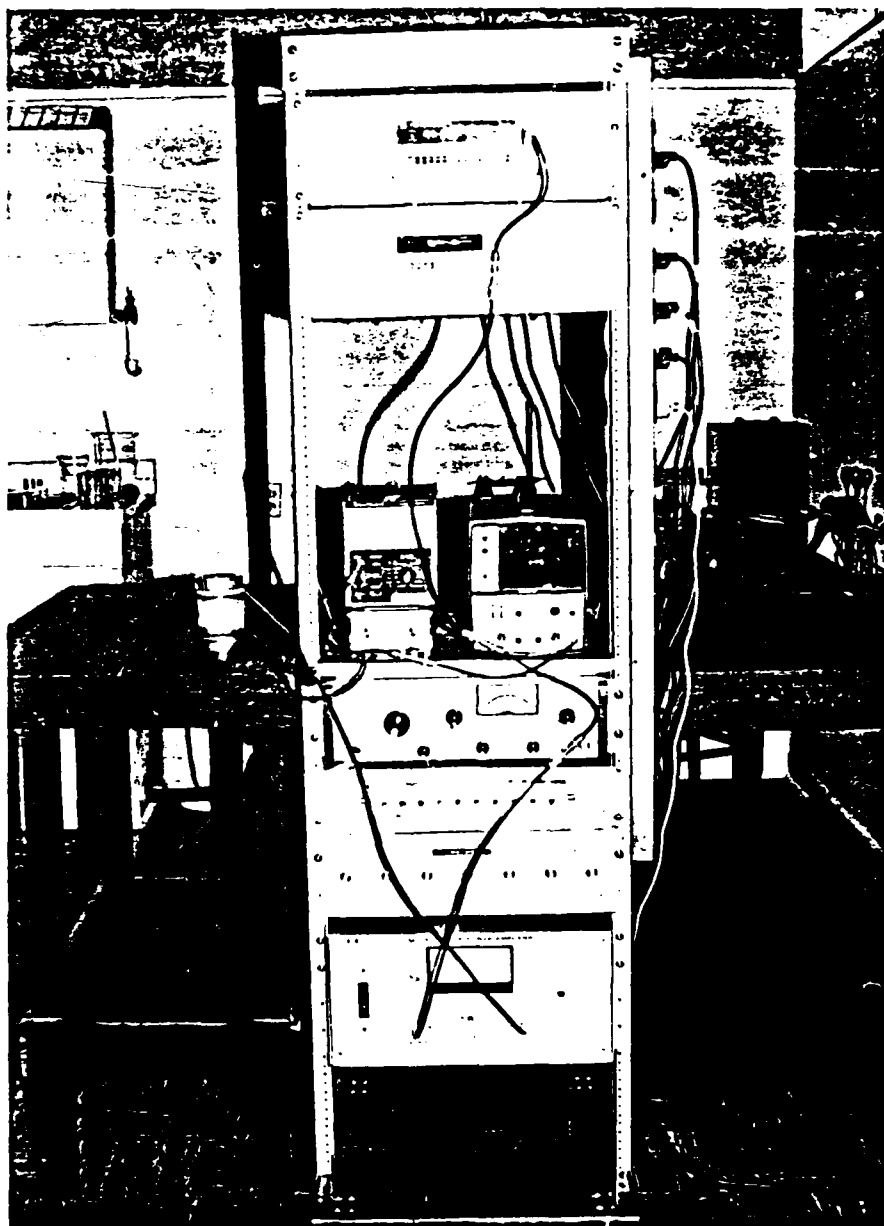


Fig. 1. A photograph of the experimental apparatus.



Fig. 2. A photograph of the cavitation cell.

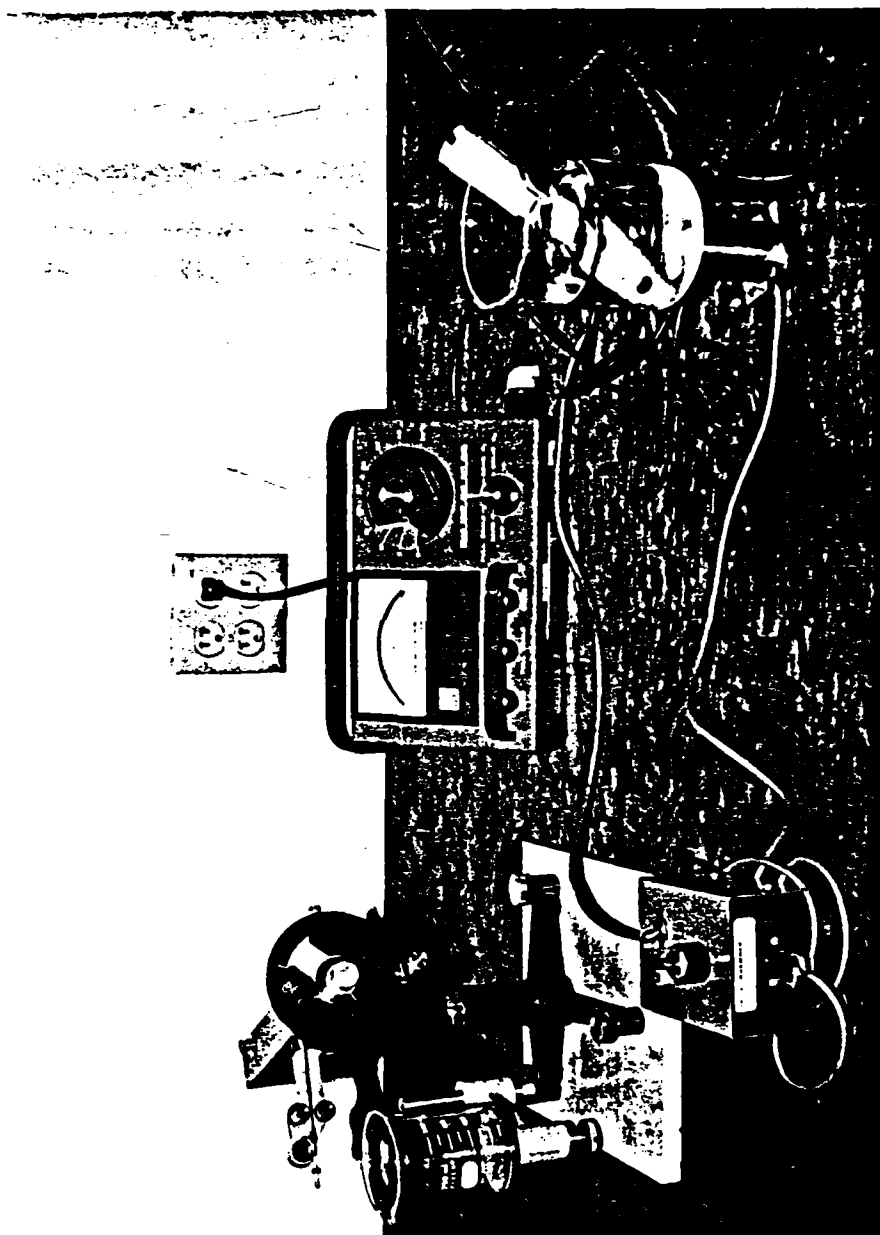


Fig. 3. A photograph of the YSI dissolved oxygen meter(right) and the Cenco-Du Nouy tensiometer(left).

## EXPERIMENTAL PROCEDURE

The principal parameters measured in this experiment were the cavitation threshold in bars, the Polyox and Guar Gum concentration in parts per million by weight, the dissolved gas concentration in percent oxygen (remaining in solution), the surface tension in dynes/cm, and the viscosity in centipoises.

To prepare the solutions it was necessary to calculate the correct amount of polymer needed for a particular concentration. This amount of polymer was then mixed with distilled water until all the polymer was in solution. The solution was degassed in a large flask attached to a vacuum system. To test for the amount of oxygen, and thus, indirectly, the dissolved gas concentration in the solution, an oxygen meter was used. The probe was placed in the solution that was under constant agitation by a magnetic stirrer (to first measure the temperature of the solution). Then the O<sub>2</sub> Solubility Factor dial was adjusted to the correct temperature setting for fresh water. For consistency of these measurements, the magnetic stirrer was turned on before a dissolved oxygen concentration reading was taken.

When the dissolved oxygen concentration for a particular solution was known, approximately 250 ml of the solution was placed in the cavitation cell. This was the amount of solution needed to completely fill the cell. To prevent cavitation on the sides of the cell, and for

consistency in cavitation threshold measurements, it was necessary to remove all visible air bubbles from the cell before the lid was placed on the system. A harmonic of the resonance frequency of the cell was used, which made the acoustic pressure amplitude a maximum in the center. The frequency used, which was held constant throughout the experiment, was 78.0 kHz and represented the  $(r, \theta, z) = (3, 0, 1)$  mode of the cell.

To allow extraneous air nuclei to settle out of the system, the solution in the cell was allowed to set for thirty minutes before any measurements were taken. At the end of thirty minutes, the system was returned to the desired frequency. The acoustic pressure was slowly increased until the output voltage from an externally mounted hydrophone was observed to rapidly decay, indicating that a cavitation event had occurred, and that the cavitation cell had detuned. In most cases, an audible pop was also detected.

The first cavitation event detected from each run was recorded as the threshold of cavitation. Data for the cavitation threshold were taken using distilled water, Polyox concentrations of 1 ppm to 100 ppm, and Guar Gum concentrations of 25 ppm to 300 ppm by weight. Data were also taken for various dissolved oxygen concentrations for each solution. It was also necessary to keep the temperature constant over the runs for maximum consistency of the thresholds.

Surface tension measurements of the solutions were made using a Cenco-DuNouy tensiometer. To obtain accurate readings it was necessary to calibrate the tensiometer. This was done through the use of a standard

liquid with a known surface tension for a given temperature. The surface tension of distilled water is known to be 73.2 dynes/cm at a temperature of 17° C, and this point was used as the primary calibration point.

The Du Nouy tensiometer is essentially a mechanical balance which measures the force required to pull a platinum ring free from the surface of the liquid. With an appropriate calibration, the device is direct reading and gives consistent readings within an accuracy of a fraction of a percent.

Viscosity readings were also taken to determine if the cavitation threshold had any dependence on the viscosity of the solution. The viscosity of the polymer solutions was determined by the use of a modified Fenske viscometer in which a known volume of fluid is allowed to flow through a narrow constriction. The viscosity of the fluid is directly proportional to the time,  $t$ , and the density,  $\rho$ , both of which can be easily measured. The viscosity,  $\eta$ , can be calculated by the use of the simple equation

$$\eta = C\rho t, \quad (1)$$

where  $C$  is a calibration constant, determined through the measurement of a fluid of known viscosity.

## THEORY

In this section a theory is introduced to explain the experimental measurements that were obtained. As the theory was not a major effort of this work, it is introduced in great brevity and with little background.

The theoretical cavitation threshold for water is on the order of 1000 bars. On the other hand, the experimental threshold for water is shown in this and other experiments to be about 5 bars, a significant difference. The commonly held explanation for this large discrepancy is that there exists in water microscopic pockets of gas, which are called nuclei, that can serve as preferential sites for liquid rupture. Therefore, a theory based on some pre-existing nucleus must be presented.

Blake<sup>5</sup> was one of the first to study this phenomenon and considered the growth of a free air bubble. Blake assumed that air bubbles were in mechanical equilibrium with their surroundings, and derived the following equation for cavitation inception:

$$P_B = P_0 \left( 1 + \frac{4}{9} X_B \left[ \frac{3X_B}{4(1 + X_B)} \right]^{\frac{1}{2}} \right), \quad (2)$$

where  $X_B = 2\sigma/P_0 R_B$ .

In this equation,  $P_B$  is the threshold acoustic pressure,  $P_0$  is the

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<sup>5</sup>Blake, F.G., Jr., Technical Memo 12, Acoustic Research Laboratory, Harvard Univ., Cambridge, Massachusetts (1949).

atmospheric pressure,  $\sigma$  is the surface tension, and  $R_B$  is the radius of the free air bubble, called the Blake radius. Blake was most certainly aware that small air bubbles dissolved and large air bubbles rise to the surface, but used this model as a first approximation.

Recently, Apfel has modified Blake's theory to include dynamic effects, taking into account the fact that time is needed for the system to react to the acoustic stress.<sup>6</sup> Apfel, unlike Blake, included viscosity, inertia, and the velocity of sound to derive a theory for the transient cavitation threshold. His expression is given as:

$$R_T = (0.13/f) \left( \frac{P_0}{\rho} \right)^{1/2} \left[ \frac{p-1}{p^{1/2}} \left( 1 + \frac{2}{3}(p-1) \right)^{1/3} \right]; \quad (3)$$

where  $p = P_T/P_0$ .

In this expression, the threshold pressure is not given explicitly in terms of  $P_T$ , but implicitly in terms of

$$p = P_T/P_0.$$

In his expression,  $P_T$  is the cavitation threshold pressure,  $P_0$  is the atmospheric pressure,  $\rho$  is the density of the liquid,  $R_T$  is the radius of the free air bubble, and  $f$  is the resonance frequency of the bubble, given by

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<sup>6</sup>Apfel, R.E., J. Acoust. Soc. of Amer. 69, 1624-1633 (1981).



$$f = \frac{1}{2\pi R_T} \left\{ \frac{3\kappa P_0}{\rho} \left[ 1 + X_r \left( 1 - \frac{1}{3\kappa} \right) \right] \right\}^{\frac{1}{2}}, \quad (4)$$

$$\text{where } X_r = \frac{2\sigma}{P_0 R_T},$$

and where  $\kappa$  is the ratio of specific heats for the gas and is equal to 1.4 for air.

In applying these equations to the experimental data, it was discovered that neither Blake's nor Apfel's equations adequately described the observed dependence of the threshold on the surface tension and, accordingly, it was necessary to introduce a theory that involved nucleation from a pocket of gas trapped in a solid particle.

Few cavitation threshold theories are applicable to normal liquids. One basic requirement for understanding cavitation is to understand the method in which air bubbles are introduced into the system. Free air bubbles existing in a liquid will either rise due to buoyancy, if sufficiently large, or collapse due to the surface tension if sufficiently small. A bubble of radius  $R$ , with a surface tension  $\sigma$ , will have an added pressure in its interior given by  $P = 2\sigma/R$ . This pressure will force the gas in the bubble into solution. For example, a bubble of 20 microns should live only a few milliseconds. Since free air bubbles can not exist for any significant period of time, the mechanism by which air bubbles are stabilized must be examined. A microscopic crevice in a mote (a solid particle) is an ideal site for small pockets of gas to be trapped. Harvey<sup>7</sup>,

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<sup>7</sup>Harvey, E.N., J. Cell. Com. Physiol. 24, 1 (1944).

Apfel<sup>3</sup>, Crum<sup>4</sup>, and others have designed simple models for gas stabilization in cracks and crevices to determine how cavitation thresholds might be influenced by these inhomogeneities.

Using a modified version of a theory by Apfel<sup>3</sup>, Crum<sup>4</sup> developed an equation that correctly predicts the variation of the acoustic cavitation threshold of water with the surface tension, dissolved gas content, and temperature. In this theory, it is assumed that there exists in the body of the liquid numerous non polar solid impurities that contain cracks and crevices in which gas pockets may be stabilized. Liquids such as distilled water contain thousands of solid impurities per cubic centimeter, and extensive and exhaustive filtration schemes are necessary to remove these particles. Scanning electron micrographs have been made of filtered solid impurities that show innumerable sites for possible gas pocket stabilization. Using the theory developed by Crum, it is possible to determine the threshold acoustic pressure required to nucleate a free gas bubble from a solid impurity. This model is often called the Harvey model of nuclei stabilization.

A mathematical model for gas stabilization for a quantity of gas trapped in a crevice<sup>8</sup> is shown in Fig. 4. The gas in the crevice does not dissolve due to the fact that the radius of curvature is concave

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<sup>3</sup>Apfel, R.E., Acoust. Soc. of Amer. 48, 1179-1186, (1970).

<sup>4</sup>Crum, L.A., Nature 278, p. 148-149, (March 8, 1979).

<sup>8</sup>Crum, L.A., Technical Report No. 178 (Michelson Physics Lab. U.S. Naval Academy, 1978).

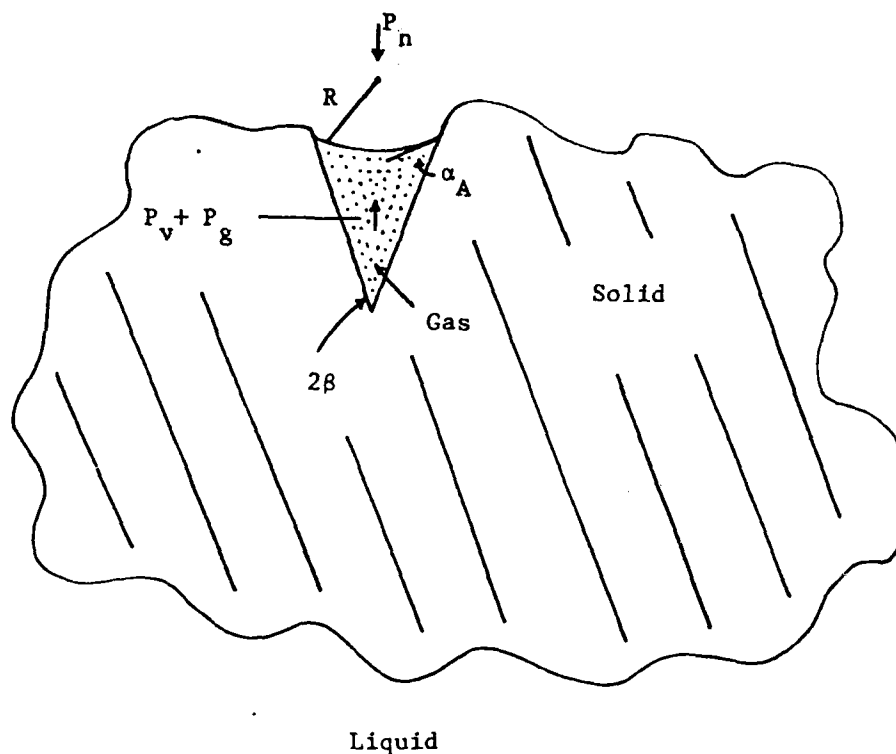


Fig. 4. Mathematical model for stabilization of a gas pocket on a solid impurity.

outwards, and the pressure due to this curvature,  $P = 2\sigma/R$ , is now applied in the outward direction. The stabilization condition in this system is given by the equation

$$P_h = P_v + P_g + 2\sigma/R . \quad (5)$$

In this equation one sees that the hydrostatic pressure  $P_h$ , is balanced by the vapor pressure  $P_v$ , the dissolved gas pressure  $P_g$ , and the most important ingredient, the surface tension "pressure"  $2\sigma/R$ .

Nucleation of a free gas bubble from a gas pocket is shown in the mathematical model in Fig. 5.

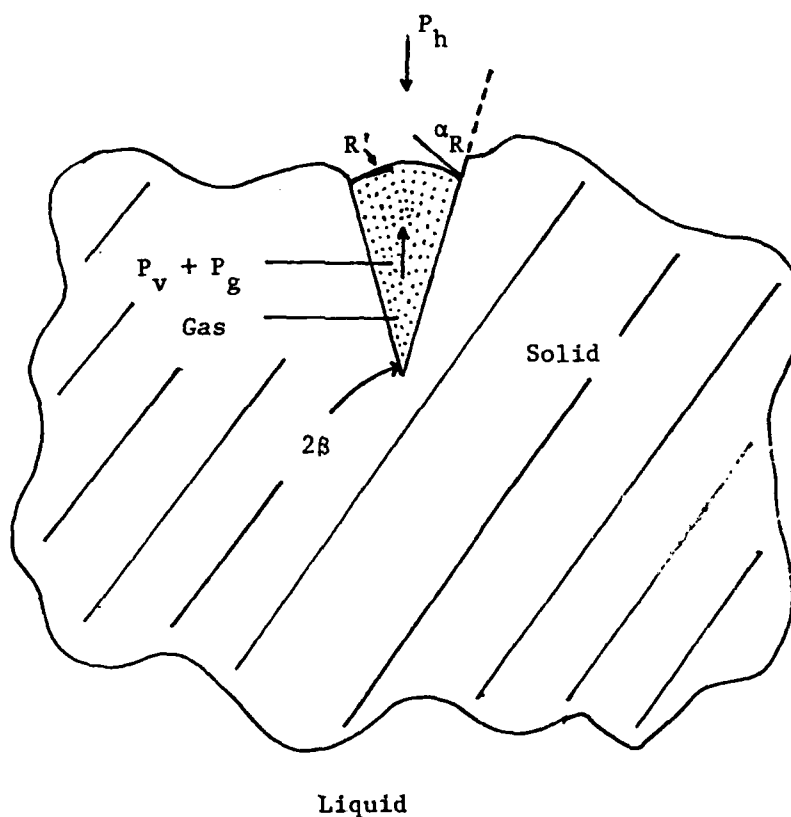


Fig. 5. Mathematical model for nucleation of a free gas bubble from a gas pocket on a solid impurity.

When the pressure in the liquid becomes sufficiently negative, as in the case of an applied acoustic pressure, the internal pressure in the nucleus becomes larger than the hydrostatic pressure. Thus, the interface bows out and, if conditions are appropriate on the interface, nucleates a free air bubble. Without going into unnecessary detail, it can be shown that the cavitation threshold, as calculated by this inhomogeneous nucleation theory, is expressed as

$$P_A = (P_h - P_v - P_g) + \frac{(P_h - P_v - P_g)}{\delta} [\cos \phi \left(\frac{C}{\sigma} - 1\right) + \sin \phi (1 - (\frac{C}{\sigma} - 1)^2)^{\frac{1}{2}}], \quad (6)$$

where

$$\delta = \cos(\alpha_A - \beta), \text{ and } \phi = \alpha_H + \beta.$$

In this equation,  $\beta$  is the half angle of the conical crevice,  $\alpha_A$  is the advancing contact angle,  $\sigma$  is the surface tension,  $C$  is a constant that depends on the surface properties of the solid (for this study it can be assumed  $C = 50$ ),  $\alpha_H$  is the hysteresis angle, and  $\phi$  is defined as the sum of the angles  $\alpha_H$  and  $\beta$ .

Since the values for the contact angles, the crevice angle, and the hysteresis angle are not exactly known, they are varied in order to obtain a best fit to the data. These constants, however, must remain within the range of permitted variations.

Viscous effects are not included in the equation to predict cavitation thresholds due to the fact that the viscosity effects can be neglected in frequencies below 3 MHz. This study was performed at a constant frequency of 78.0 kHz.

## RESULTS AND DISCUSSION

In this section, the major aspect of this work is introduced. The experimental measurements of the cavitation threshold are compared to the theoretical predictions as a function of such parameters as surface tension, polymer concentration, dissolved gas concentration, and viscosity.

One of the principal parts of this study was the dependance of the acoustic cavitation threshold on the liquid surface tension. To examine this dependance, it was first necessary to measure the surface tension for various concentrations of the long chain polymers Polyox and Guar Gum. Surface tensions were measured for distilled water, solutions of distilled water and Polyox ranging from 1 ppm to 100 ppm by weight, and solutions of distilled water and Guar Gum ranging from 25 ppm to 300 ppm by weight. The measurements were made at a constant temperature of 17°C.

Fig. 6 shows the dependance of the surface tension on concentration for aqueous solutions of Polyox and Guar Gum. It is obvious from these curves that an additive such as a long chain polymer will significantly decrease the surface tension of water. It is also seen that the surface tension is lowered a substantial amount initially, but as more polymer is added a rapid saturation appears to occur.

Next, the dependance of the acoustic cavitation threshold on the concentration of the polymer was examined. In Figs. 7 and 8, the cavitation threshold versus the concentration of the polymers Polyox and Guar Gum

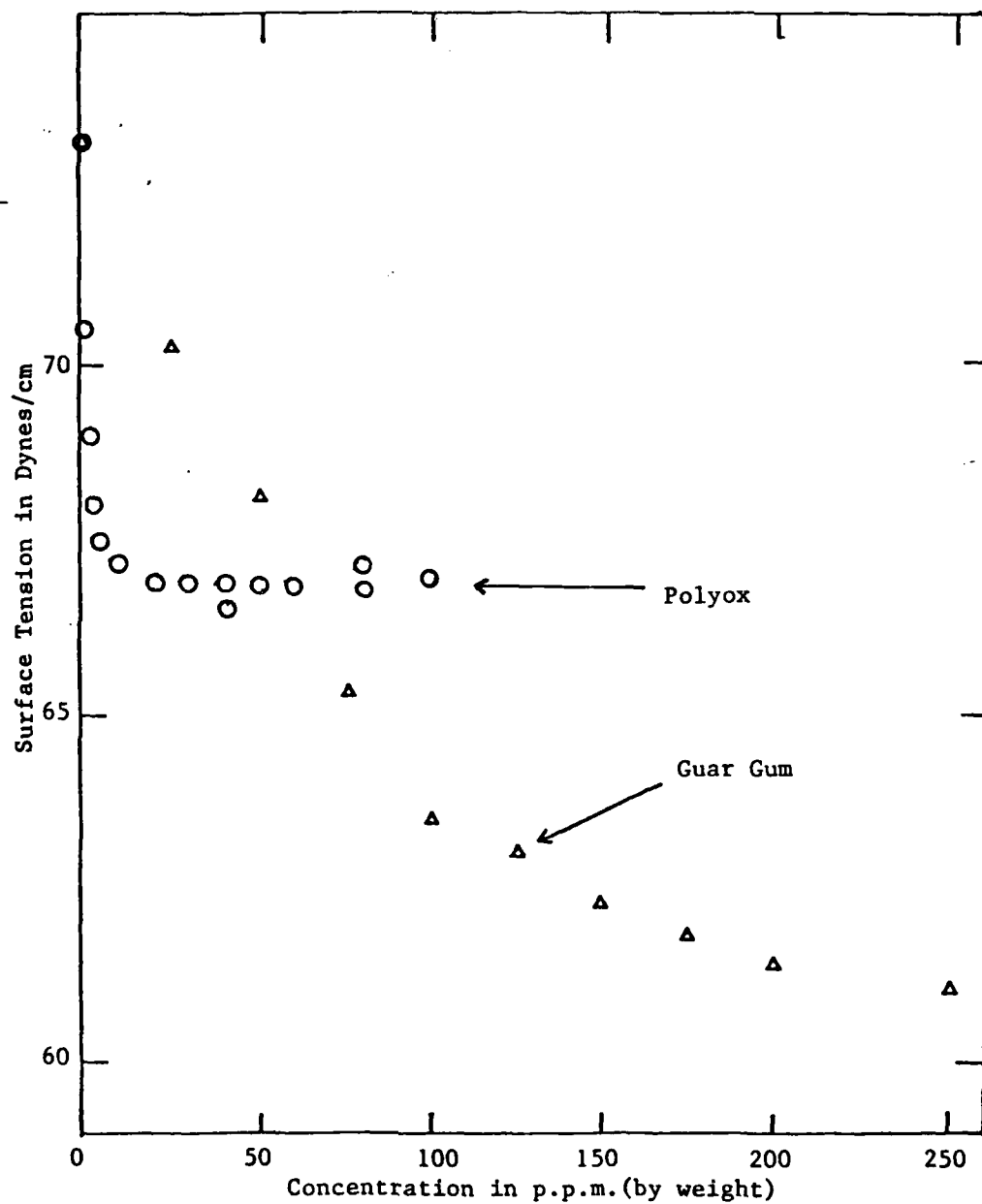


Fig. 6. Variation of surface tension with concentration of polymer for Polyox and Guar Gum.

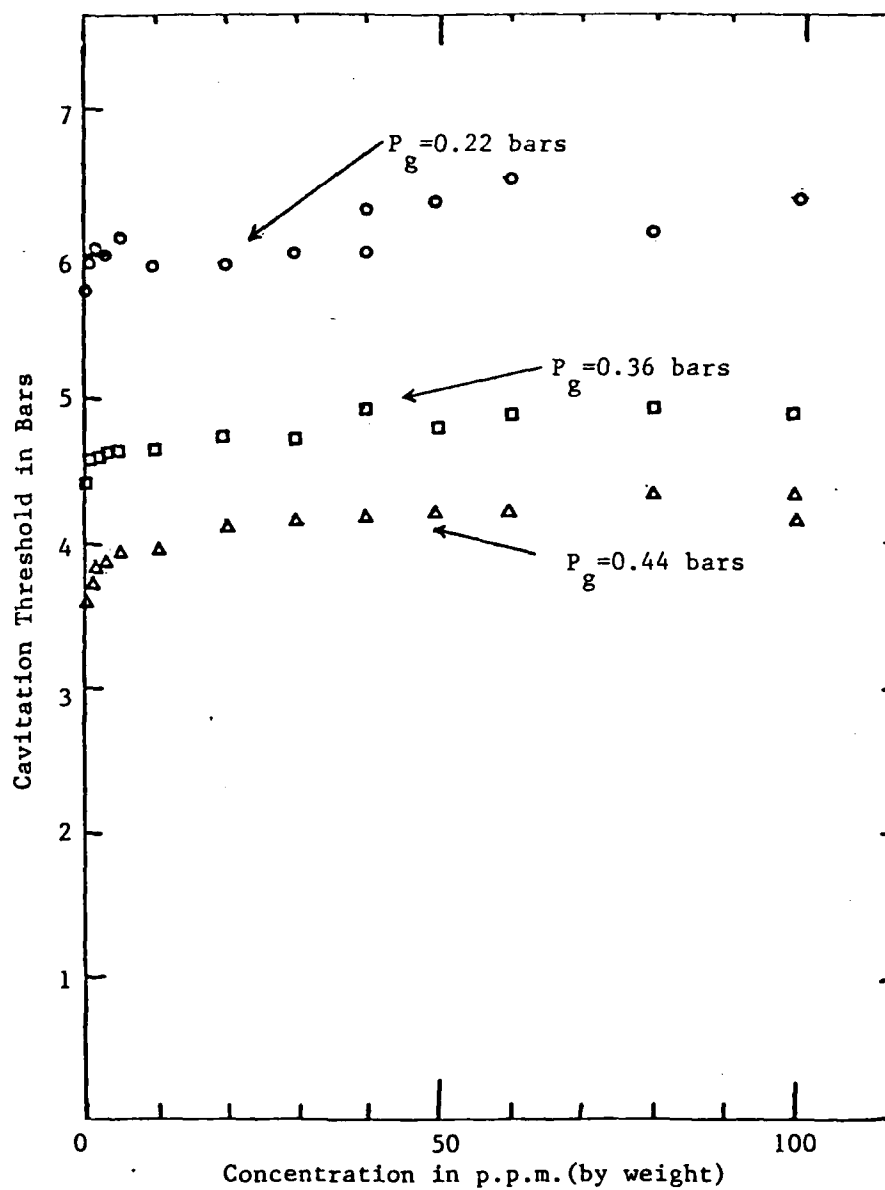


Fig. 7. Variation of the cavitation threshold with concentration of Polyox.



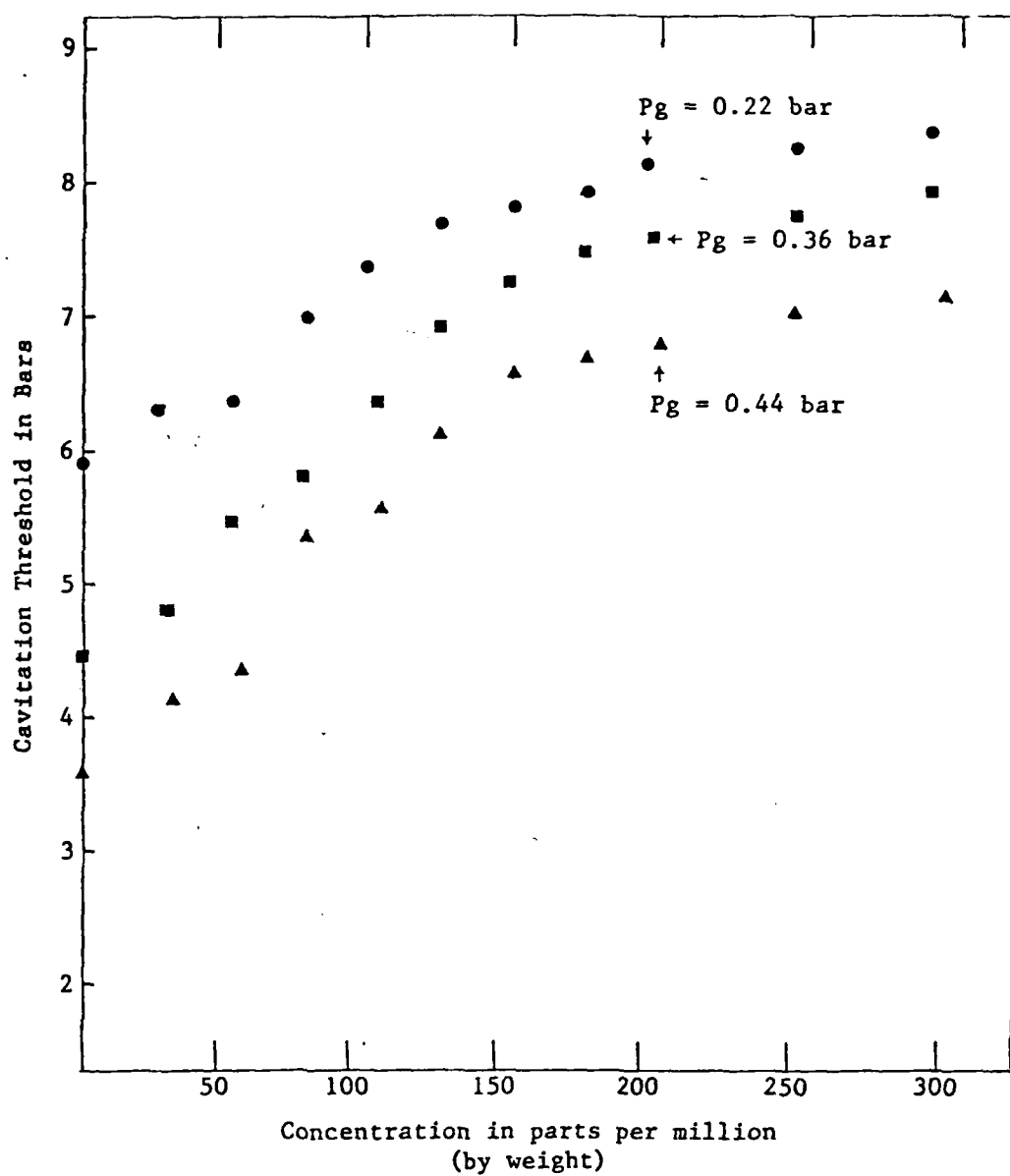


Fig. 8. Variation of Cavitation thresholds with concentration in Guar Gum

respectively is shown for three different values of dissolved gas concentration. It was observed from comparing the curve for the cavitation threshold versus concentration of Polyox (Fig. 7) to the curve of surface tension versus concentration of Polyox (Fig. 6), that both curves were similar, both approaching a constant value for the same concentration of Polyox, and thus an obvious dependance of the acoustic cavitation threshold on the surface tension is implied. The curves for the variation of the cavitation threshold and the liquid surface tension with concentration for Guar Gum (Fig. 8) is similar to those for Polyox, implying that acoustic cavitation thresholds have an important dependance on the surface tension in all long chain polymers.

To determine whether the cavitation threshold has any dependance on viscosity, it was necessary to measure the viscosity of the polymer solutions directly, as no data on this dependance was available. The viscosity of the polymer additives in water as a function of concentration is shown in Fig. 9. The curves for Polyox and Guar Gum both show that viscosity increases as concentration increases, and that the increase in viscosity is greater the higher the concentration. When one compares this dependance on concentration with the dependance of the cavitation threshold on concentration, it is unlikely that viscosity has a significant effect on the cavitation threshold. This tends to verify our theoretical prediction that cavitation thresholds depend on the surface tension and not on the viscosity.

To verify that the cavitation threshold actually has a strong

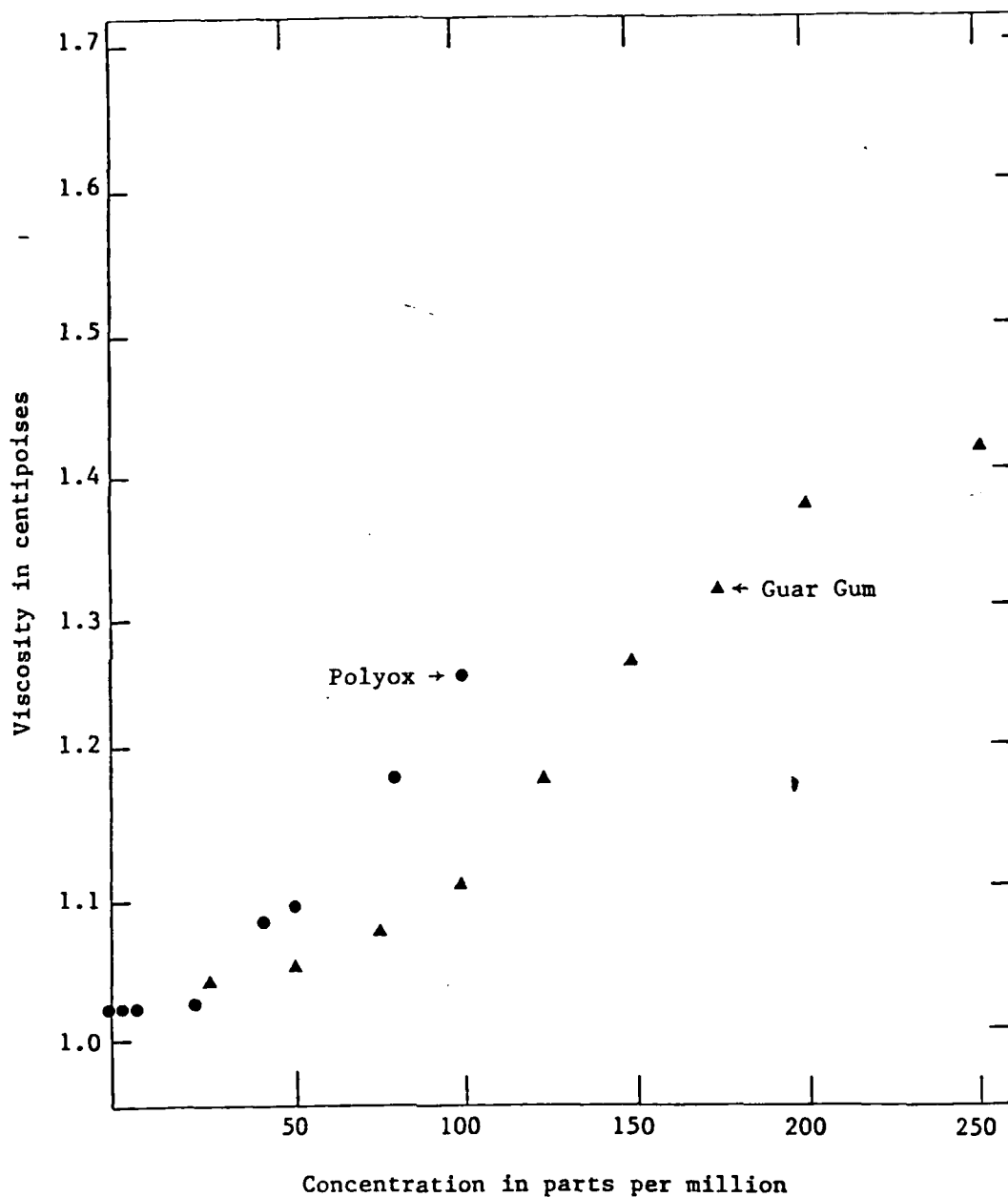


Fig. 9. Variation of viscosity with concentration of polymer for Polyox and Guar Gum.

dependence on the surface tension, experimental measurements were made for aqueous solutions of Polyox and Guar Gum. Figure 10 shows curves for the variation of the cavitation threshold with surface tension in Polyox for three different values of the dissolved gas concentration. The surface tensions ranged from 66.5 dynes/cm to 72.5 dynes/cm, and the three data sets are for dissolved gas concentrations of 22%, 36%, and 44%. Cavitation threshold data were taken at a constant temperature of 20° C. Figure 11 shows the cavitation threshold versus surface tension for Guar Gum. These three curves have surface tensions ranging from 60.6 dynes/cm to 72.5 dynes/cm, and show the cavitation thresholds for a constant dissolved gas concentration of 22%, 36%, and 44%. In both sets of curves, there is an inverse dependence of the cavitation threshold on the surface tension, i.e. for lower surface tensions there are larger thresholds. Since cavitation is generally associated with the growth of a small nucleus, one would expect that the threshold would be lower for lower surface tensions. In order to understand this unexpected behavior, it is necessary to examine the predictions of the available theories.

Over the years, several theories have been developed in an attempt to predict the acoustic cavitation threshold as a function of various liquid parameters. One of the first of these theories, a static theory originated by Blake, and discussed in the Theory section of this study, expresses the cavitation threshold as a function of the surface tension, the atmospheric pressure, and the radius of the nucleus, which is assumed

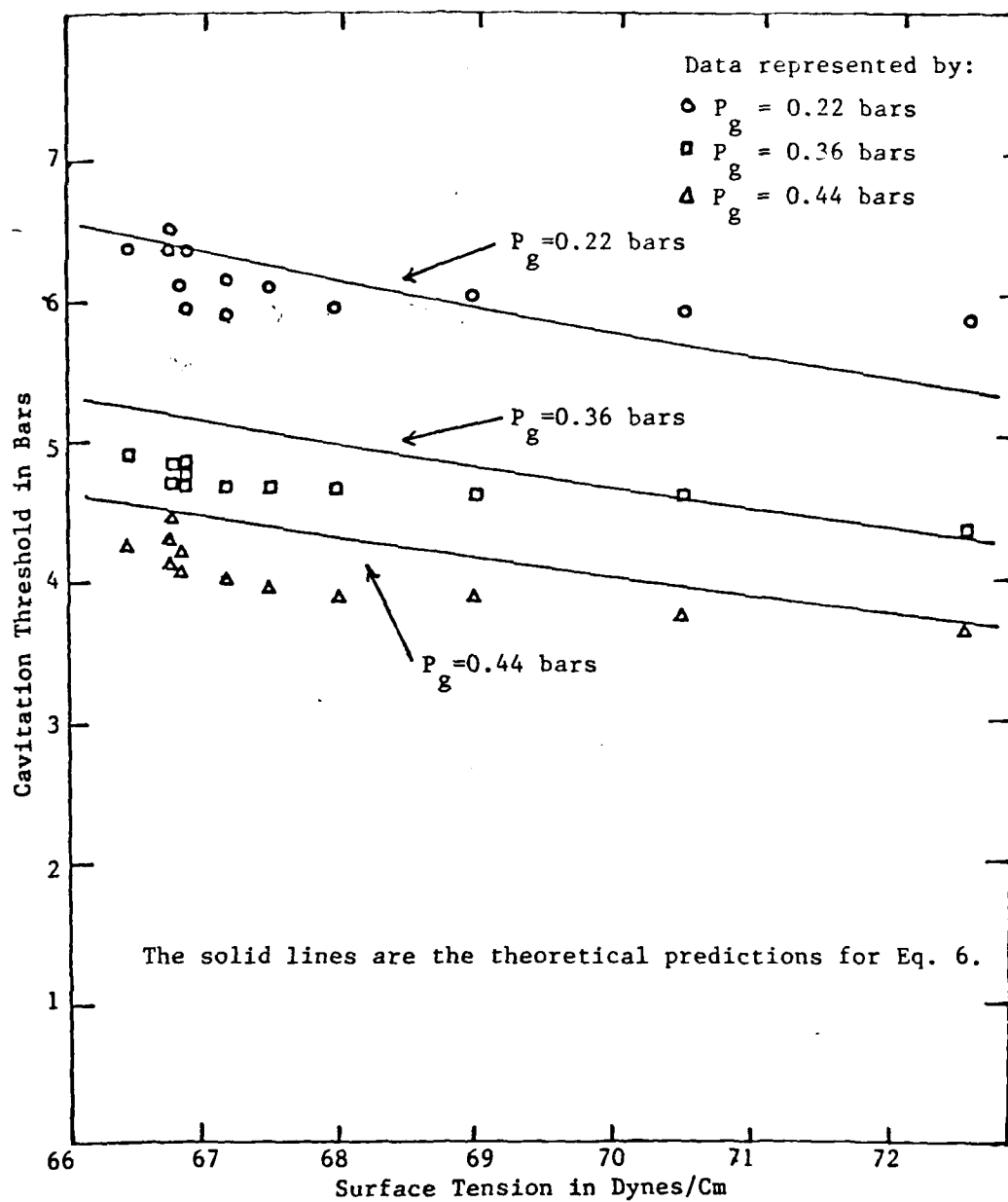


Fig. 10. Variation of the cavitation threshold with surface tension in Polyox.

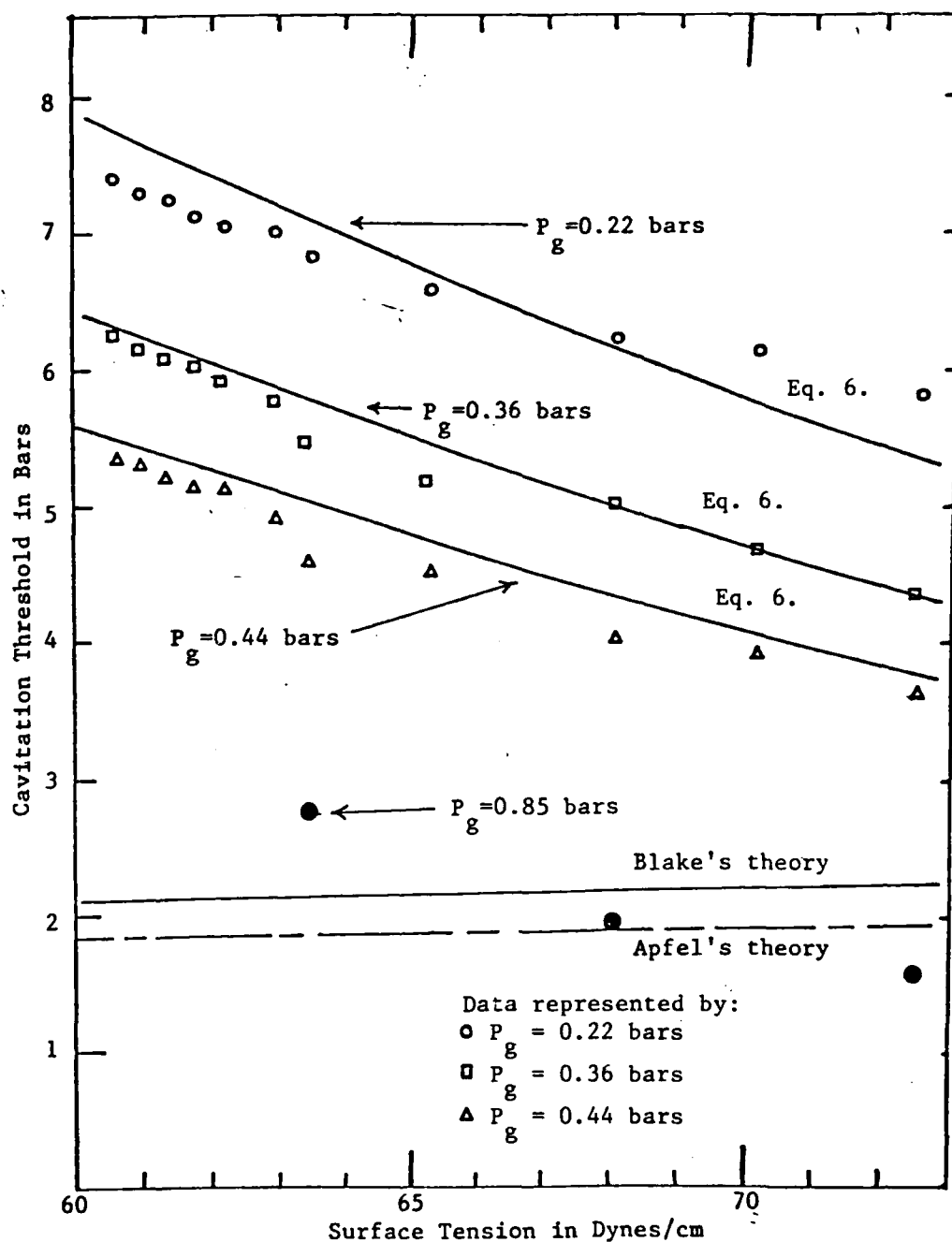


Fig. 11. Variation of the cavitation threshold with surface tension in Guar Gum.

to be a free air bubble. Blake's expression for the cavitation threshold as a function of these parameters was expressed earlier as Eq. 2. Figure 11 shows the relationship between Blake's theoretical prediction for the cavitation threshold and the experimental data. The solid line represents Blake's theoretical prediction for an atmospheric pressure of  $1.0 \times 10^6$  dyn/cm and a bubble radius of  $5.0 \times 10^{-6}$  cm. This particular value of the radius was chosen here to give an approximate fit to the data. The experimental data values represent dissolved oxygen concentrations of 22%, 36%, 44%, and 85% of the dissolved oxygen concentration at atmospheric pressure. It is seen that Blake's theory does not correctly predict the observed dependence of the cavitation threshold on the surface tension.

A more recent theory, developed by Apfel, and also discussed earlier, attempts to account for the dynamic effects in the growth of a cavitation nucleus. This particular theory of Apfel also assumes the cavitation nucleus to be a free air bubble. The expression for the threshold as determined by Apfel's theory was expressed earlier as Eq. 3. The radius used for Apfel's theory was chosen to be  $2.2 \times 10^{-6}$  cm to achieve an order of magnitude fit to the experimental data. Apfel's theoretical prediction for the cavitation threshold as a function of surface tension is also shown in Fig. 11. It is observed that Apfel's dynamic theory likewise does not predict the observed dependence of the cavitation threshold on the surface tension. It is seen in general that the free air bubble theories predict a direct dependence of the threshold on the surface tension, in contrast to the observed inverse dependence. In

order to adequately explain these data, it is necessary to apply a theory based upon nucleation from a pocket of gas stabilized in a crevice of a solid particle.

The final theory to be reviewed in this study, developed by Crum<sup>4</sup> based upon an earlier approach of Apfel<sup>3</sup>, was given earlier as Eq. 6. Shown in Figs. 10 and 11 are the predictions of Eq. 6 for various values of the dissolved gas concentration. Note that excellent agreement is obtained between theory and experiment for the data given here. The theory is tested further in Figs. 12 and 13 which show the cavitation threshold versus dissolved gas concentration in aqueous solutions of Polyox and Guar Gum respectively. For the Polyox case the two sets of experimental data are for two different surface tensions, 66.5 dynes/cm and 72.5 dynes/cm, that were held constant throughout the experiment. For the experiment using Guar Gum, the constant surface tensions were 63.5 dynes/cm and 72.5 dynes/cm. Data was taken for dissolved gas concentrations between 22% and 85%. The theoretical predictions are the solid lines, and are labeled to correspond with the set of data. The close fit of the theoretical prediction to the experimental data indicates the applicability of this theory.

In order to apply the nucleation theory to the experimental data it was necessary to numerically fit three parameters. These parameters

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<sup>3</sup>Apfel, R.E., Acoust. Soc. of Amer. 48, 1179-1186, (1970).

<sup>4</sup>Crum, L.A., Nature 278, 148-149, (March 8, 1979).



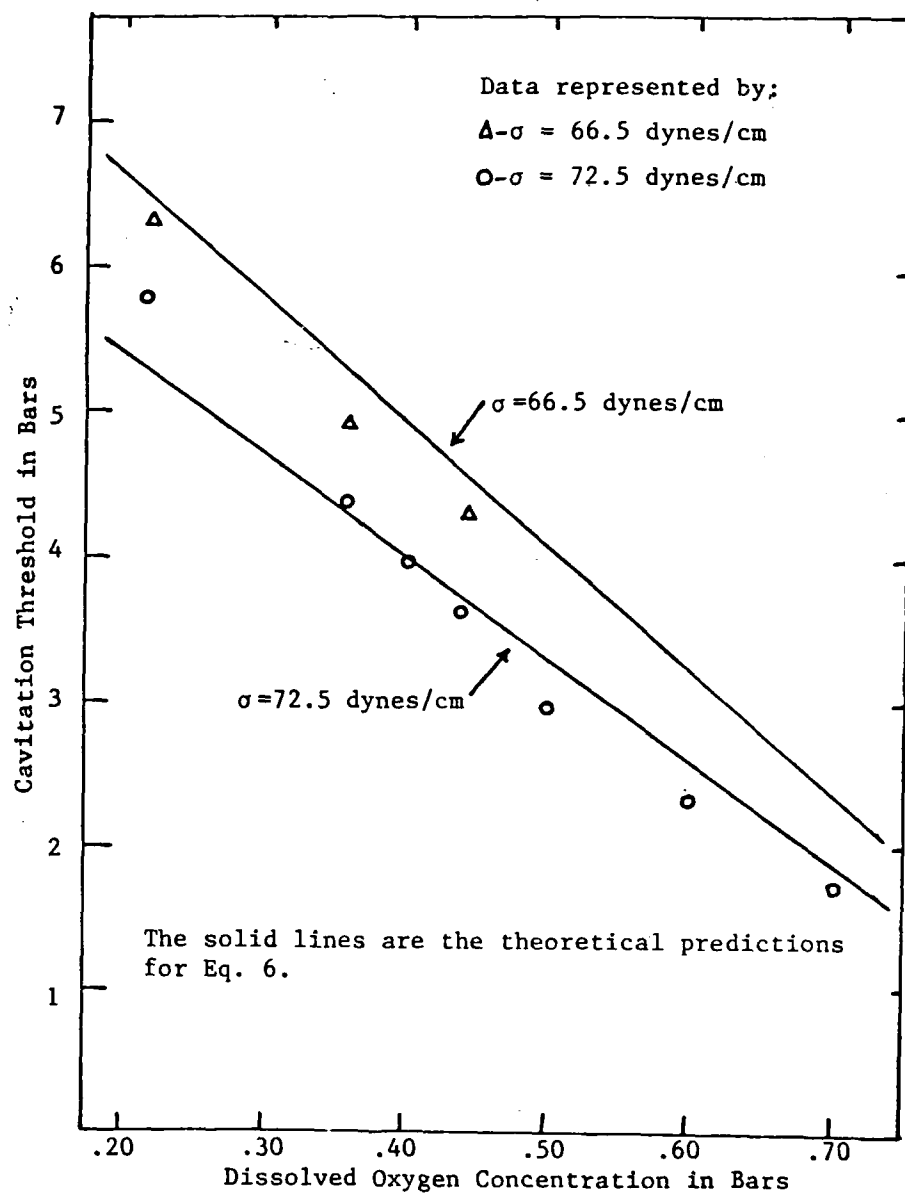


Fig. 12. Variation of the cavitation threshold with dissolved oxygen concentration in Polyox.

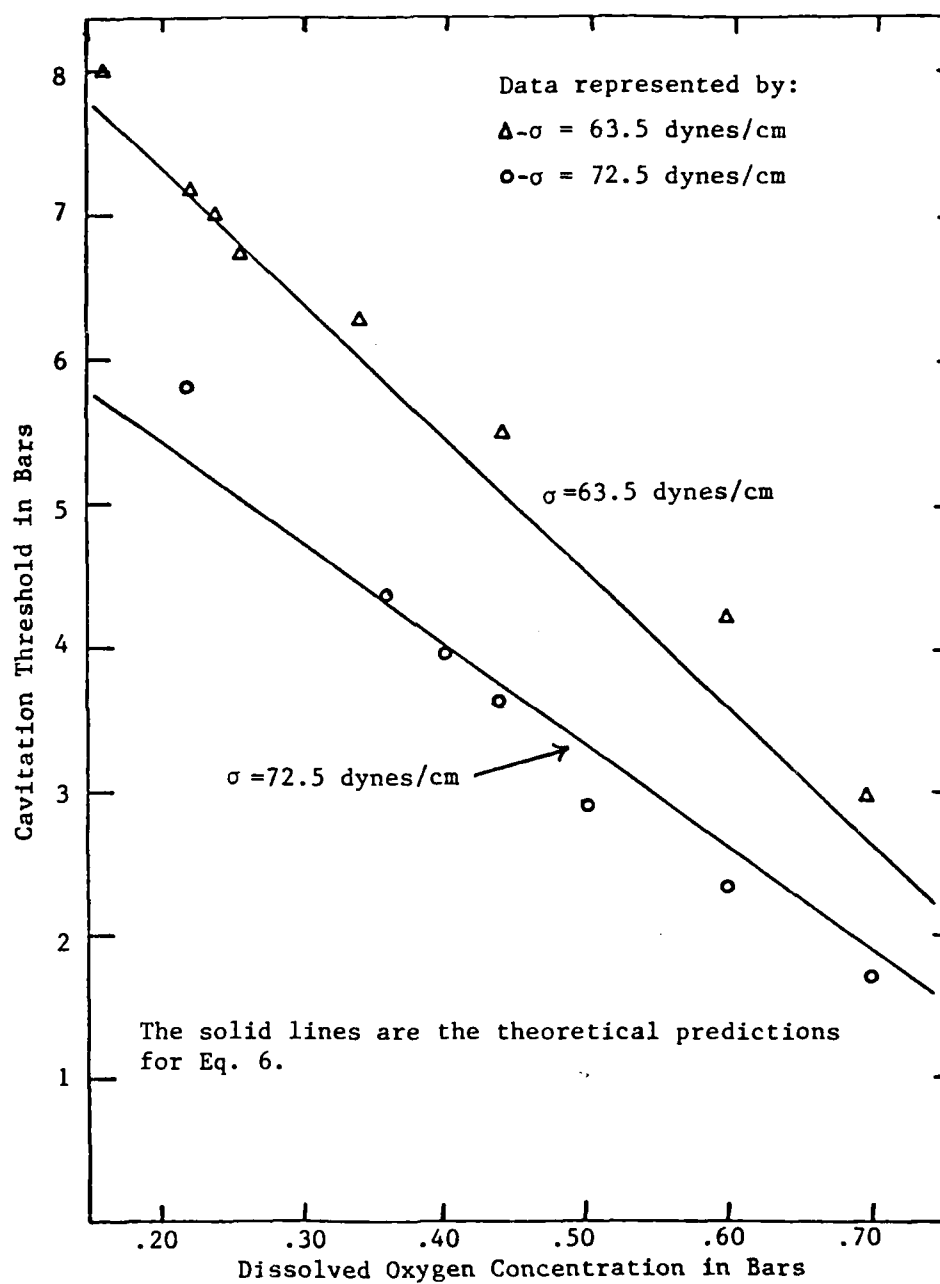


Fig. 13. Variation of the cavitation threshold with dissolved oxygen concentration in Guar Gum.

were the half angle of the conical crevice  $\beta$ , the advancing contact angle  $\alpha_A$ , and the hysteresis angle  $\alpha_H$ . The advancing contact angle has been measured to have values on the order of  $100^\circ$  for non-polar solids. Bargeman<sup>9</sup> lists values of  $\alpha_A$  for four non-polar solids has an average of  $106^\circ$ , and a standard deviation of  $6^\circ$ . The advancing contact angle for water on paraffin wax is an average of  $106^\circ$ , and a standard deviation of  $6^\circ$ . The advancing contact angle for water on paraffin wax is known to be approximately  $106^\circ$ .<sup>10</sup> Therefore,  $\alpha_A$  was selected to be  $106^\circ$  for this study. The crevice angle  $\beta$ , must be small for adequate stabilization. A value of  $\beta = 13.8^\circ$  was selected to give  $\delta = 0.039$  (see Theory section for definition of these constants). Values of the hysteresis angle of water plus surfactant on non-polar solids were measured by Furmidge.<sup>11</sup> He obtained values ranging from  $14^\circ$  to  $44^\circ$  for water plus surfactants on white beeswax. To obtain a good fit to the data used in this study,  $\alpha_H$  was chosen to be  $19.2^\circ$ , making  $\phi = \alpha_H + \beta = 33^\circ$ . These parameters are very similar to the parameters chosen by Crum<sup>4</sup> when his nucleation theory for cavitation thresholds was first tested.

It is observed that the acoustic cavitation threshold has a strong dependance on surface tension when the dissolved gas concentration is

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<sup>4</sup>Crum, L.A., Nature 278, 148-149, (March 8, 1979).

<sup>9</sup>Bargeman, D. and Van Voorst Vader, R., J. Coll. Sci. 42, 467-472 (1973).

<sup>10</sup>Bargeman, D., J. Coll. Sci. 40, 344-348, (1972).

<sup>11</sup>Furmidge, C.G.L., J. Coll. Sci. 17, 309-324, (1962).

held constant, (Figs. 10 and 11) and that the cavitation threshold has a strong dependance on dissolved gas concentration when the surface tension is held constant (Figs. 12 and 13). Since the free air bubble theories can not account for either of these variations, one must conclude that the nuclei present in these experiments were not free air bubbles. Further, since the Harvey model can account for these variations, one should give preference to this model for cavitation threshold prediction in aqueous solutions.

## ERROR ANALYSIS AND LIMITS OF ACCURACY

Error in this experiment was caused by a variety of sources. First, the main difficulty in mixing the solutions was insuring that all of the polymer went into solution. For concentrations of over 100 parts per million Guar Gum, and over 60 parts per million Polyox, it was necessary to boil the distilled water to force the polymer into solution. After the solution was thoroughly mixed, it was necessary that the solution be cooled to a constant temperature before taking any measurements. There probably was some polymer that came back out of solution once the mixture cooled, although this condition was minimized.

Second, error was probable in the dissolved gas concentration readings. The temperature of the solution needed to be held constant throughout the experiment, and this was particularly so in testing for the dissolved gas concentration. The reason for this temperature control was that the  $O_2$  Solubility Factor dial had to be set at the correct temperature of the solution before the dissolved oxygen concentration reading could be taken. While the dissolved oxygen concentration was taken, it was also necessary to continually agitate the solution. Some error could have occurred if the dissolved oxygen concentration in the solution was not consistent throughout. Another error dealing with the oxygen concentration was due to the 30 minute wait from the time the solution was placed in the cell to the time when the cavitation threshold

readings were taken. During this time the oxygen concentration probably increased slightly since the solution had some, although minimal, contact with air.

Third, there were several possible causes of error in the cavitation threshold measurements. The driving frequency was kept at the resonance frequency of 78.0 kHz for the threshold measurements to be consistent. It was possible for the frequency to drift a small amount, and it was possible for this changing temperature to detune the system, making it necessary to monitor the frequency throughout the experiment. If the frequency were not at resonance, the acoustic pressure was not at a maximum, causing the measured values for the cavitation threshold to be high. The rapidity at which the acoustic pressure was increased also determined, to some small extent, the values of the cavitation threshold. If the pressure was increased too fast, higher values would be obtained, and if the pressure was increased too slowly, lower values would result. Therefore it was necessary to increase the acoustic pressure within the cell at a constant rate, preferably very slowly, to minimize the error.

Once a cavitation event occurred, many small nuclei would be created and they would move about freely in the liquid. These microbubbles should normally have dissolved in a few milliseconds, but with surface tension additives in the solution, there is a possibility that some of these nuclei could live for times on the order of seconds. To minimize possible error, time was allowed for these nuclei to dissolve, in that

after a cavitation event was detected, a repeated attempt was not made for several seconds.

Next, error could have been caused by the changing temperature and atmospheric conditions. It has been shown that the temperature<sup>4</sup> and changing atmospheric pressure<sup>3</sup> can affect the cavitation threshold. This error was minimized by making the measurements at a constant temperature as nearly as possible.

Finally, there were possible causes of error in the surface tension measurements. The major possible cause of error was the possibility of foreign material contaminating the solutions, and thereby altering the surface tension. Contamination could have been introduced into the system through unclean glassware, an unclean platinum ring, and foreign material from the air, all having a detrimental effect. Other possible causes of error were in the calibration, and in the difficulty of keeping the index indicator at zero.

The limits of accuracy for all the parts of this experiment are given in the remainder of this section.

The surface tension of any particular solution could be measured accurately to the nearest 0.05 dynes/cm, with possible fluctuations of 0.2 dynes/cm, for surface tensions ranging from 60.6 dynes/cm to 72.5 dynes/cm. With this consistency, surface tension measurements could have a maximum error of 0.3%.

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<sup>3</sup>Apfel, R.E., Acoust. Soc. of Amer. 48, 1179-1186, (1970).

<sup>4</sup>Crum, L.A., Nature 278, 148-149 (March 8, 1979).

The accuracy of the concentration of polymer in solution depended upon the accuracy of the scale used to measure the amount of polymer, and the accuracy of the method used to measure the volume of distilled water. Since the scale was accurate to 0.0001 grams and the volume was accurate to 10 ml in 1500 ml, the final solution had an error of approximately 1%.

The cavitation threshold measurements were accurate to the nearest 0.03 bars, which in most cases was less than 1% error.

Finally, the most accurate readings in this experiment were the frequency at which measurements were taken and the viscosity of the solutions. The frequency was accurately measured, using a Hewlett Packard universal counter, to the nearest 0.01 kHz, a 0.01% error. The least accurate measurement used to calculate the viscosity was the time measurement. Therefore, the viscosity measurements were as accurate as human reaction time allowed. The time measured was accurate to the nearest tenth of a second. Since the time for the solution to flow through the viscometer ranged between 233.4 seconds and 341.4 seconds, the error in the calculated viscosity values ranged only from 0.03% to 0.04%.



## CONCLUSIONS

The acoustic cavitation threshold in polymer solutions has been investigated as a function of surface tension, viscosity, concentration of dissolved polymer additives and dissolved gas concentration.

In this study, it was shown that cavitation threshold theories based upon nucleation from free air bubbles do not predict the observed dependance of the threshold on surface tension. Therefore, it was necessary to devise a stabilized nucleus model before an adequate explanation of the data could be made. The predictions of the cavitation threshold made from the stabilized nucleus or Harvey model proved to be adequate in explaining the observed variation with surface tension, polymer concentration, and dissolved gas concentration. It was also shown that the cavitation threshold had no apparent dependance on viscosity.

The good fit of the theoretical prediction to the experimental data shows that the physical properties of the fluid are very important in predicting the cavitation threshold. Hoyt<sup>1</sup> and Ellis<sup>2</sup> felt that nuclei in the liquid were not important in predicting the reduced cavitation thresholds observed in their studies. Hoyt<sup>1</sup> states, "It seems clear,

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<sup>1</sup>Hoyt, J.W., J. Fluids Engr. 106-112 (1976).

<sup>2</sup>Ellis, A.T., J.G. Waugh, and R.Y. Ting, J. Basic Engr. Series D, 92, 459-466 (1970).

then, that an explanation of the reduced cavitation inception in polymer solutions must lie in changed fluid dynamics rather than fluid physical properties." In this study, it has been shown that the acoustic cavitation threshold does depend on changed fluid properties.

Also in this study, the same concentrations of Polyox and Guar Gum correspond to different surface tensions. It was found that if the surface tension measurements were the same, the same cavitation threshold would result. This observation implies that the cavitation threshold is very much dependent upon the surface tension, and not the type of polymer additive.

Analysis of the cavitation thresholds versus the dissolved gas concentration showed that the smaller the amount of dissolved gas in solution, the higher the value of the cavitation threshold. This is to be expected in a Harvey model since less gas in the system would correspond to nucleation sites in which the air-liquid interface had advanced down into the crevice, and thus would require a higher negative acoustic pressure to nucleate a vapor cavity. Other models for nucleation, such as the free air bubble models, would not predict this behavior.

Thus, it was shown in this study that an adequate explanation of the effect of polymer additives on the cavitation threshold can only be given if a theoretical expression based upon nucleation from a Harvey model is used to calculate the threshold.

TABLE I  
SURFACE TENSION VERSUS CONCENTRATION IN  
POLYETHYLENE OXIDE AT  $T = 17^{\circ}\text{C}$

CONCENTRATION ppm	SURFACE TENSION (dynes/cm)
0	73.2
1	70.5
2	69.0
3	68.0
5	67.5
10	67.2
20	66.9
30	66.9
40 (stirred)	66.9
40 (boiled)	66.5
50 (boiled)	66.9
60 (boiled)	66.8
80 (stirred)	67.1
80 (boiled)	66.8
100 (stirred)	66.9
100 (boiled)	66.9

TABLE II  
SURFACE TENSION VERSUS CONCENTRATION  
IN GUAR GUM AT  $T = 17^{\circ}\text{C}$

CONCENTRATION ppm	SURFACE TENSION (dynes/cm)
1	73.2
25	70.2
50	68.1
75	65.3
100	63.5
125	63.0
150	62.2
175	61.8
200	61.4
250	61.0
300	60.6

TABLE III  
DATA NECESSARY TO CALCULATE VISCOSITY  
IN POLYOX FOR  $\eta = C\rho t$   
 $C = .0045059$

CONCENTRATION	DENSITY	TIME	VISCOSITY
ppm	(g/ml)	(sec)	(centipoises)
0	.99823	223.4	1.005
5	.99824	223.8	1.007
10	.99824	226.9	1.021
20	.99825	229.8	1.034
40	.99827	240.1	1.080
50	.99828	243.0	1.093
80	.99831	260.8	1.173
100	.99833	277.6	1.249

TABLE IV  
DATA NECESSARY TO CALCULATE VISCOSITY  
IN GUAR GUM FOR  $\eta = Cpt$   
 $C = .0045059$

CONCENTRATION	DENSITY	TIME	VISCOSITY
ppm	(g/ml)	(sec)	(centipoises)
0	.99823	223.4	1.005
25	.99826	230.1	1.035
50	.99828	232.3	1.045
75	.99831	237.8	1.070
100	.99833	244.2	1.099
125	.99836	260.5	1.172
150	.99838	281.0	1.264
175	.99841	291.6	1.312
200	.99843	303.9	1.367
250	.99848	312.4	1.406
300	.99853	341.4	1.536

TABLE V  
CAVITATION THRESHOLD VERSUS DISSOLVED OXYGEN  
CONCENTRATION IN DISTILLED WATER

DISSOLVED OXYGEN CONCENTRATION	CAVITATION THRESHOLD
in bars	in bars
0.16	6.56
0.22	5.78
0.30	5.35
0.36	4.39
0.40	3.95
0.44	3.62
0.50	2.89
0.60	2.27
0.62	2.00
0.70	1.66
0.85	1.54

TABLE VI  
CAVITATION THRESHOLD VERSUS POLYMER  
CONCENTRATION IN POLYOX

POLYMER CONCENTRATION in ppm	CAVITATION THRESHOLD FOR DISSOLVED OXYGEN CONCENTRATIONS		
	in bars		
	22%	36%	44%
1	5.93	4.57	3.73
2	6.04	4.58	3.86
3	5.94	4.65	3.87
5	6.08	4.65	3.95
10	5.88	4.64	3.96
20	5.90	4.74	4.13
30	5.94	4.69	4.14
40 (stirred)	6.03	4.91	4.18
40 (boiled)	6.31	4.90	4.23
50 (boiled)	6.36	4.78	4.19
60 (boiled)	6.52	4.87	4.18
80 (stirred)	6.10	4.95	4.35
80 (boiled)	6.09	4.87	4.32
100 (stirred)	6.34	4.78	4.14
100 (boiled)	6.37	4.84	4.31



TABLE VII  
CAVITATION THRESHOLD VERSUS POLYMER  
CONCENTRATION IN GUAR GUM

POLYMER CONCENTRATION in ppm	CAVITATION THRESHOLD FOR DISSOLVED OXYGEN CONCENTRATIONS		
	22%	36%	44%
25	6.17	4.87	4.15
50	6.27	5.45	4.34
75	6.80	5.69	5.35
100	7.18	6.27	5.45
125	7.47	6.75	6.03
150	7.57	7.04	6.41
175	7.66	7.21	6.51
200	7.86	7.35	6.60
250	8.00	7.50	6.80
300	8.10	7.66	6.96

TABLE VIII  
CAVITATION THRESHOLD VERSUS DISSOLVED OXYGEN  
CONCENTRATION FOR 50 PPM GUAR GUM

DISSOLVED OXYGEN CONCENTRATION	CAVITATION THRESHOLD
in bars	in bars
0.22	6.27
0.26	6.03
0.35	5.59
0.36	5.45
0.40	4.87
0.44	4.34
0.53	3.37
0.64	2.89
0.65	2.41
0.85	1.93

TABLE IX  
CAVITATION THRESHOLD VERSUS DISSOLVED OXYGEN  
CONCENTRATION FOR 100 PPM GUAR GUM

DISSOLVED OXYGEN CONCENTRATION	CAVITATION THRESHOLD
in bars	in bars
0.16	8.00
0.22	7.21
0.24	7.04
0.26	6.70
0.34	6.27
0.36	6.27
0.44	5.45
0.51	5.35
0.60	4.24
0.70	2.99
0.82	2.80

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#### BIOGRAPHICAL SKETCH OF THE AUTHOR

James Eugene Brosey, son of Wilfred and Valaire Brosey, was born on February 15, 1958. He attended high school at Parkville Senior in Parkville, Maryland, and graduated in 1976. Then he attended David Lipscomb College in Nashville, Tennessee, and graduated magna cum laude with a B.S. in Physics in 1980. James Brosey is a member of the physics honorary society, Sigma Pi Sigma. In 1980, he was awarded a non-service fellowship and a research assistantship at the University of Mississippi. He is presently interested in singing, running, biking, and camping. James Brosey has held many jobs while earning his B.S. and Masters degree. His present positions are laboratory instructor and research assistant at the University of Mississippi Physics Department. Before this he worked as a laboratory instructor, math tutor and phone host at David Lipscomb College in Nashville, Tennessee from January, 1977 to May, 1980. James Brosey plans to pursue a career in physics research, and some day return to graduate school to work for a doctorate degree. His present address is Box 2526, University, Mississippi, 38677.

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